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Vineyard mulching as a climate change adaptation measure: Future simulations for Alentejo, Portugal

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A R T I C L E I N F O

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A B S T R A C T

Climate change projections for the next decades are expected to bring important challenges to the Portuguese viticulture. More specifically, for the wine region of Alentejo, in Southern Portugal, the projected warming and drying are expected to have detrimental impacts on grapevine physiology and ultimately on yields. The present study assesses the adaptation potential of mulching for maintaining current grapevine yield levels in the region. For this purpose, the STICS process-based crop model was used to simulate future (2021–2080) grapevine yields in the 8 sub-regions of Alentejo (with Denomination of Origin). Several datasets for weather variables, soil characteristics, topographic features and management practices were defined independently for each sub-region. Simulations comprise both non-mulching and mulching experiments over the next 60 years, under the climate change scenario RCP8.5. Although both non-mulching and mulching simulations suggest a gradual yield decrease in the future, mulching mitigates these decreases by 10 to 25%. Furthermore, the results show that mulching can reduce the yield decreasing trend, from −0.75%/year to −0.66%/year. In effect, mulching is expected to provide yield gains over the full simulated time period, being the benefits particularly apparent towards the end of the target period (2061–2080; warmest years of simulation). Mulching is a cost-effective adaptation measure that may be easily adopted by growers on the short-term. Nonetheless, this strategy alone might not be enough to fully mitigate yield losses and additional / complementary measures should be envisioned to warrant the sustainability of the Alentejo winemaking sector under futures climates.

1. Introduction

Climate change brings important challenges to viticulture. Some of the major risks may be driven by the projected rise in air temperatures and the decrease in soil water availability (Fraga et al., 2016; Santos et al., 2017). Particularly in Southern European winemaking regions, the increasing intra- and inter-annual climatic variability are an emerging concern for the sector stakeholders (OIV, 2015). Additionally, the synergistic effects of warming and drying projected for these regions may further threaten this important socioeconomic sector (Fraga et al., 2018). The increasing frequency of occurrence of extreme weather events, such as droughts, prolonged rainfall periods (Cyr et al., 2010), heat waves (White et al., 2006), late frosts or cold spells (Menzel et al., 2011; Molitor et al., 2014; Yadollahi, 2011), hail and thunderstorms (Spellman, 1999), may cause negative effects on both grapevine yield and berry quality attributes and, in more extreme conditions, crop failure.

Several world winemaking regions are located in areas with typical Mediterranean-type climates (Jones et al., 2005). In effect, these regions are already under very stressful conditions for plant growth, characterized by warm and dry grapevine growing season (Jones et al., 2005; Kottek et al., 2006; Toth and Vegvari, 2016). It has been shown that these stresses can be relieved and even counteracted by certain management practices that can be applied by growers (Fraga et al., 2017; Keller, 2010a). Some of these practices include leaf area control (Harbertson and Keller, 2012; Keller et al., 2011), changes in the tillage systems and soil management (Bahar and Yasasin, 2010; Kvaternjak et al., 2008), or even the application of irrigation (Chaves et al., 2007; Chaves et al., 2010; dos Santos et al., 2003; Ferreira et al., 2012). Given the projected future warming and drying of climatic conditions in the Southern European winemaking regions, there is an increasing need for a better understanding of the potential benefits of these practices.

One potential adaptation measure that needs to be considered and further studied is the application of mulches or mulching (Chan et al., 2010). Mulches are organic or inorganic products that may be placed on the soil surface. Mulching reduces soil compaction and retains soil moisture, as it protects the soil surface, regulates soil temperature and reduces evaporation (Chen et al., 2007; Novak et al., 2000). In addition

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to saving water, mulching improves soil quality and increases its organic matter content. Mulches may also be beneficial for combatting pests and stopping weed development, thus reducing water competition. Moreover, vineyards with mulch tend suffer less heat and water stresses. Previous studies showed that mulching may help to maintain yield levels under adverse climatic conditions, while decreasing water requirements (DeVetter et al., 2015). Furthermore, mulching is an affordable agricultural technology for sustainable soil and land management, promoting a reduction of soil erosion, and can be easily adopted by most farmers. Although potential benefits of mulching have already been reported, no study has yet investigated the impacts of mulching application under climate change scenarios. Thus, a better understanding of the impact of mulching on future yields is required.

The present study will be focused on Alentejo, a large viticultural region in inner southern Portugal. This region has undergone a remarkable development over the recent decades and is currently the leading region in terms of non-fortified wine production. It is characterized by a dry sub-humid Mediterranean climate and is classified as a climate change hotspot, i.e. "*a region for which potential climate change impacts on the environment or different activity sectors can be particularly pronounced*" (Giorgi, 2006). In fact, it is highly vulnerable to climate change owing to the high risk of desertification under future semi-arid conditions, low quality of soils and high temperatures (Costa et al., 2017; Jones et al., 2011; Santos et al., 2017). Despite the growing irrigated areas, namely using water from the vast Alqueva dam and other important water reservoirs, the majority of the region is still not irrigated and viticulture is mostly rainfed. As a result, climate suitability for grapevine growth and development is threatened in Alentejo (Coelho et al., 2013) and suitable adaptation measures are thereby needed to ensure the future sustainability of this crop.

The present study aims at assessing the impacts of mulch application as a climate change adaptation measure in the viticultural region of Alentejo, Portugal. Therefore, the present study objectives are four-fold: 1) to simulate mulching application using a dynamic crop model, specifically adapted to viticulture in Alentejo; 2) to assess potential benefits of different mulch types, particularly regarding yields; 3) to analyze the impacts of mulch treatments on Alentejo spatial and temporal grapevine yield variability; and 4) to compare the range of these potential benefits regarding different bioclimatic indicators under future climate change scenarios.

2. Material and methods

2.1. Study region

Alentejo is a large viticultural region in southern Portugal characterized mostly by flatlands, with a relatively homogenous warm and dry climate. The Alentejo viticultural region is currently divided into 8 sub-regions (with Denomination of Origin: DO): Portalegre, Borba, Redondo, Reguengos, Vidigueira, Évora, Granja-Amareleja and Moura (Fig. 1). The vineyard land cover is mostly concentrated within these sub-regions. Vineyard area in this region has been increasing since the 1980s (Linear Trend; LT ~500 ha/year), despite some recent slight decreases, and it is currently around 23 thousand ha (IVV, 2015). This is one of the most productive wine regions in Portugal, with a wine production of around 1 million hl, which has also been increasing in the last years (LT ~38,000 hl/year) (IVV, 2015). Regarding the main cultivars, Aragonez (syn. Tempranillo), Trincadeira and Castelão are the most important red varieties, while Roupeiro, Antão-Vaz and Arinto are the main white varieties (IVV, 2015).

2.2. The STICS dynamical crop-model

Modelling was achieved using the STICS (*Simulateur mulTIdisciplinaire pour les Cultures Standard*) crop model (Brisson et al., 2008). This model is, presently, one of the few process-based crop models that may be applied to grapevine simulation (perennial crop). STICS requires a large number of input parameters, such as weather data, soil characteristics, terrain features, along with varietal information and management practices. All these inputs are then used to simulate grapevine growth, phenological development and yields (among other outputs). The model has been tested and validated for grapevines under different climates, management practices, soils and irrigation regimes (Coucheney et al., 2015; Fraga et al., 2015, 2018; Valdes-Gomez et al., 2009). Furthermore, this model has previously been used in assessing the impacts of climate change on European viticulture (Fraga et al., 2016). Given the model skillfulness in simulating grapevine yields (Fraga et al., 2015; García de Cortazar-Atauri, 2006; Valdes-Gomez et al., 2009), it was used herein to assess the benefits of mulching strategies as a climate change adaptation measure at regional level.

Fig. 1. Geographical boundaries of the viticultural regions in Portugal. The 8 viticultural sub-regions in Alentejo are highlighted (Portalegre, Borba, Redondo, Reguengos, Vidigueira, Évora, Granja-Amareleja and Moura).

2.2.1. Crop model simulation inputs

Datasets for i) daily weather variables, ii) soils properties, iii) topographic features, iv) management practices and v) cultivar data were used as model inputs. These data were retrieved for each sub-region in Alentejo separately, using the centroid method (i.e. the value for the geographic centroid of each sub-region was extracted using a geographic information system).

2.2.2. Weather variables

The daily weather variables used were: minimum and maximum 2-m air temperature (°C), solar radiation (MJ m^{-2}), precipitation (mm),

wind speed ($m\,s^{-1}$), water vapor pressure (hPa) and atmospheric CO_2 concentration (ppmv). These variables were obtained for both a recent-past period (1981–2005) and a future period (2021–2080, 60 years) and were subsequently used as input in STICS. Recent-past daily data were obtained from the SMHI-RCA4 (Samuelsson et al., 2011), Regional Climate Model (RCM), driven by the ERA-interim reanalysis (Dee et al., 2011). These CORDEX reanalysis runs, assimilate observational datasets, thus representing available observations (Dee et al., 2011). Regarding the climate change projections, the SMHI-RCA4 RCM was forced by the MPI-M-MPI-ESM-LR (Giorgetta et al., 2013) Global Climate Model (GCM). These data were collected for 2021–2080 under the Representative Concentration Pathway – RCP8.5 (van Vuuren et al., 2011) at 0.125° spatial resolution (approximately 13.8 km near the equator). Future data were subjected to a bias correction methodology, i.e. “Empirical Quantile Mapping”, using the R® package “downscaleR” (Cofiño et al., 2017), and using the recent-past data as a reference. Under this future scenario, CO_2 emissions are expected to continuously rise until the end of the century. Although other, less severe, future scenarios were also considered (e.g. RCP4.5), a previous study revealed similar impacts on Portuguese viticulture (Fraga et al., 2016). The MPI-M-MPI-ESM-LR GCM was selected due to its high performance in simulating atmospheric mechanisms over the North Atlantic and Western Europe (Santos et al., 2016).

2.2.3. Soil and terrain characteristics

Soil characteristics for each sub-region in Alentejo were obtained from the Harmonized World Soil Database (HWSD) (FAO and ISRIC, 2014; Jones and Thornton, 2015), which incorporates the latest updates of soil information. HWSD provides soil profile data of topsoil (0–30 cm) and subsoil (30–100 cm), such as physical-chemical properties (e.g. bulk density, albedo and pH). Based on soil profiles, soil hydraulic properties (e.g. water retention capacity) are estimated using pedotransfer functions (Brisson et al., 2009; Saxton and Rawls, 2006). Regarding topography, the GTOPO30 digital elevation model (https://lta.cr.usgs.gov/GTOPO30), distributed by the U.S. Geological Survey, is employed to assess the elevation, aspect classes and slope degree (e.g. for the assessment of surface runoff).

2.2.4. Cultivar and management practices

One of the most common cultivar in Alentejo and in Portugal as a whole – Aragonez (syn. Tempranillo) (IVV, 2015) was selected to perform these simulations. As Portuguese native varieties are not included in the STICS default package, these data were integrated taking into account two previous studies (Fraga et al., 2015; Fraga et al., 2018). Additionally, viticultural management practices were equally defined for all sub-regions. For this purpose, the selected trellis system was Cordon and vine density was set to 4000 vines ha^{-1}, which are common values in Portuguese vineyards. Harvest dates were determined automatically by STICS, when berry water content reached 77% (probable alcohol level of roughly 12.5%v/v) (García de Cortazar-Atauri et al., 2009).

2.2.5. Crop model runs

The STICS model was initialized using the abovementioned input variables. Two types of model runs were performed: non-mulching vs. mulching simulations. Model runs were focused simply on the future time period, as the STICS performance under current climates has previously been evaluated and revealed good agreement with field data. Hence, a model run was carried out for each region (8 regions), for each year in the future period (60 years; 2021–2080) and for each mulching type/strategy (12, including no-mulching), corresponding to 5760 combinations / simulations. The selection of mulching materials and amounts (Table 1) followed the guidelines available in Brisson et al. (2008), which are generally in agreement with viticultural management practices found in several studies worldwide (Chan et al., 2010; DeVetter et al., 2015; Dilley and Nonnecke, 2007; Judit et al., 2011).

Table 1
Mulch types (11) used in the STICS simulation, along with fresh matter amount ($t\,ha^{-1}$) and water content (%), following Brisson et al. (2008).

Mulch type	Fresh matter ($t\,ha^{-1}$)	Water content (%)
Cereals (straw)	9	7
Sugarbeet (leaves and crowns)	40	90
Grain maize (stalks)	12	25
Soybean (straw and roots)	5	10
Proteaginous pea (foliage and roots)	4	10
Rapeseed (roots, pods and straw)	6	10
Wheat, rye (cereals)	8	80
Mustard (cruciferous)	10	70
Phacelia (cruciferous)	15	80
Radish, oil seed (cruciferous)	15	80
Ryegrass (grass)	18	80

2.2.6. Non-mulching vs. mulching simulations

As previously mentioned, in order to evaluate the effects of mulching application under future climates, a preliminary non-mulching simulation was performed. Firstly, the simulated yield timeline from 2021 to 2080 was assessed at regional (Alentejo) and sub-regional (8 sub-regions) scales. The yield change time series were subsequently normalized (relative departure from the annual maximum yield) in order to account for uncertainties in STICS yield simulations under future climates. Secondly, the same methodology was applied in the mulching simulations, but the normalization was also performed using non-mulching maximum yields to enable a comparison of yield magnitudes. Hence, for the full period, the spatial median yield and interquartile yield range are analyzed for both non-mulching and mulching simulations.

2.3. Future climate projections for Alentejo

Climate model data were also used herein to provide a characterization of future climatic conditions in the Alentejo winemaking region. For this purpose, a set of bioclimatic indices with relevance to viticulture was first assessed. The selected bioclimatic indicators were: growing season mean temperature (GST); growing season precipitation sum (GSP); number of days with temperature above 36 °C (T36); number of days with precipitation below 1 mm (PR1); thermal stress index (FTEMP); hydric stress index (SWFAC). GST is a widely used viticultural index to assess the thermal potential of a given region and has also shown a good correspondence to high-quality wine regions worldwide (Jones, 2006). GSP is a good indicator of water availability during the growing season, likely influencing yields (Blanco-Ward et al., 2007; Hardie and Considine, 1976). Limited growth under excessively high temperatures and severe dryness was also taken into account by the T36 and PR1 indices, which are used to evaluate extreme weather conditions. Temperatures above 36 °C are commonly considered as a upper limit at which grapevine physiological activities can be compromised (Brisson et al., 2008), while many days with precipitation below 1 mm can also promote high soil water deficits. Lastly, SWFAC and FTEMP are STICS indicators of plant water and temperature stresses, respectively (Brisson et al., 2008). These indices vary from 1 (low stress) to 0 (high stress), i.e. lower values correspond to higher stress.

2.4. Influence of mulching regarding different climatic conditions

In order to properly analyze the potential benefits of mulching under different climatic conditions, such as extreme heat and severe drought, a subsequent analysis was performed. The 60 year time series (2021–2080) of yield differences between mulching and non-mulching simulations was categorized into 3 classes (terciles): high, medium and low yield changes. Subsequently, these 3 classes where compared

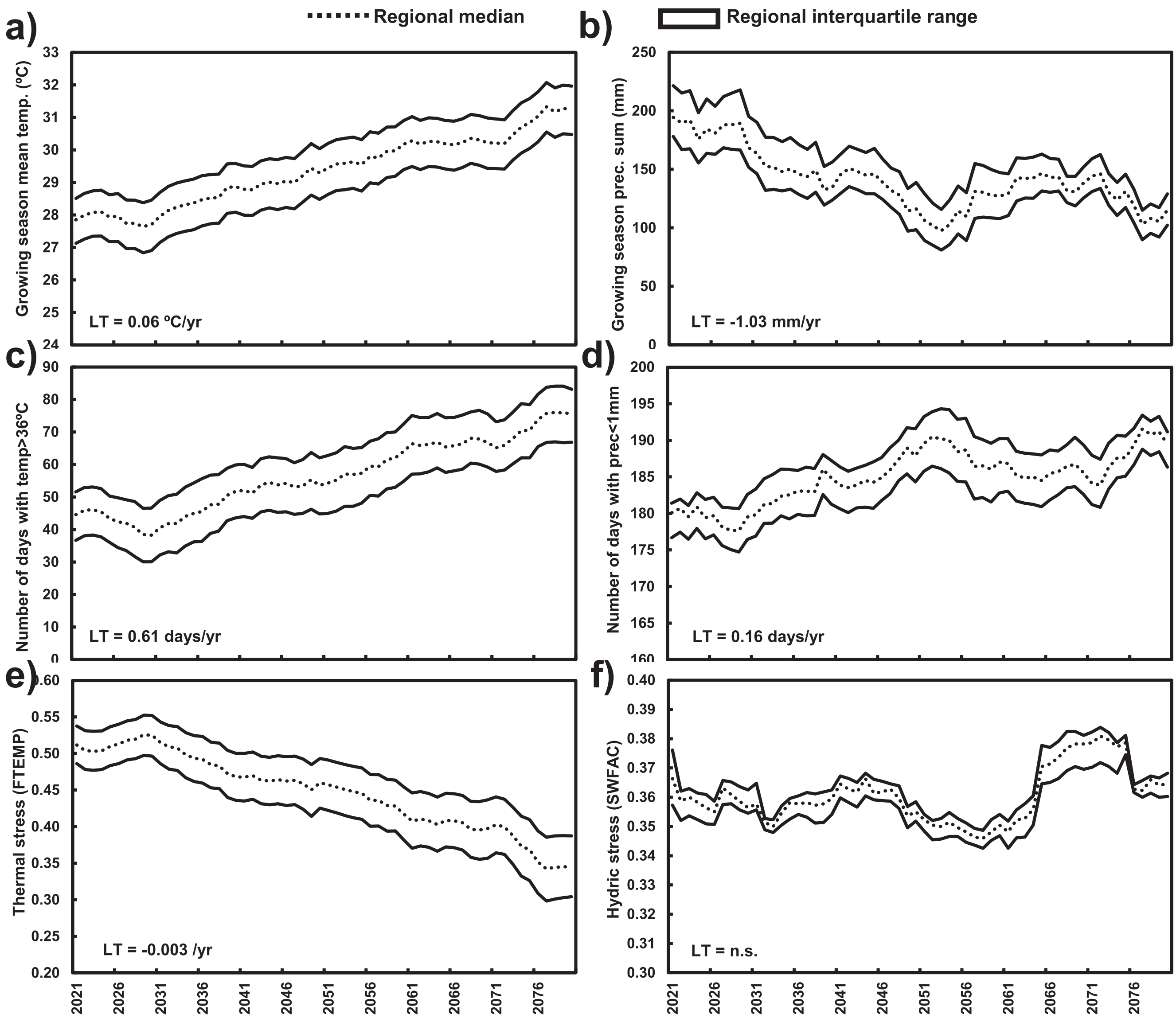

Fig. 2. Projections for the regional median and interquartile ranges (25th to 75th percentiles) over the future period (2021–2080) for: a) growing season mean temperature; b) growing season precipitation sum; c) number of days with temperature above 36 °C; d) number of days with precipitation below 1 mm; e) thermal stress index (FTEMP); f) hydric stress index (SWFAC). Linear trends (LT) are also shown.

regarding the different bioclimatic indicators (GST, GSP, T36, PR1, SWFAC, FTEMP) to identify the benefits of mulching under different conditions. Comparing yield gains/decreases in years with high/low stress may also give clues on the efficiency of this particular adaptation measure.

3. Results

3.1. Future projections for bioclimatic indicators

Fig. 2 depicts the simulated temporal evolution of the bioclimatic indicators over the future period and for the Alentejo. The median and interquartile range of the 8 DO sub-regions are shown along with the respective linear trends from 2021 to 2080 (Mann-Kendall trend test was applied to attest the trend significance, *p*-value < 0.001). GST for the Alentejo region reveals an increase towards the end of the selected period of 0.06 °C/year (Fig. 2a). The median GST of 28 °C in 2021 will gradually increase to 32 °C by 2080 (Fig. 2a). Regarding GSP, Alentejo is projected to undergo a decrease of 1.03 mm/year (Fig. 2b). However, this trend is significantly more pronounced until 2050, followed by a slight stabilization until 2080. Median GSP by 2080 is projected to be of approximately 100 mm throughout this region. Regarding extreme weather conditions, T36 is projected to increase from ~45 days in 2021 up to 70 days in 2080 (LT = 0.61 days/year), while projections for PR1 show a less pronounced increase of 0.16 days/year (Fig. 2c, d). Regarding the plant stress indicators, thermal stress is projected to steadily increase towards the end of the period, whereas a stabilization of the water stress is projected (Fig. 2e, f). SWFAC shows the single non-significant trend among the selected indices.

While the hydric-related indices (GSP, PR1 and SWFAC) reveal a relatively heterogeneous behavior throughout the time series, the thermal indices (GST, T36 and FTEMP) show a much more homogenous development, revealing increases until 2080. Conversely, the hydric indices display more severe values around the mid-21st century, followed by a stabilization, or even a slight recovery, until the end of the target period.

3.2. Future yield projections (non-mulching simulations)

Normalized yield change projections (non-mulching) show a linear

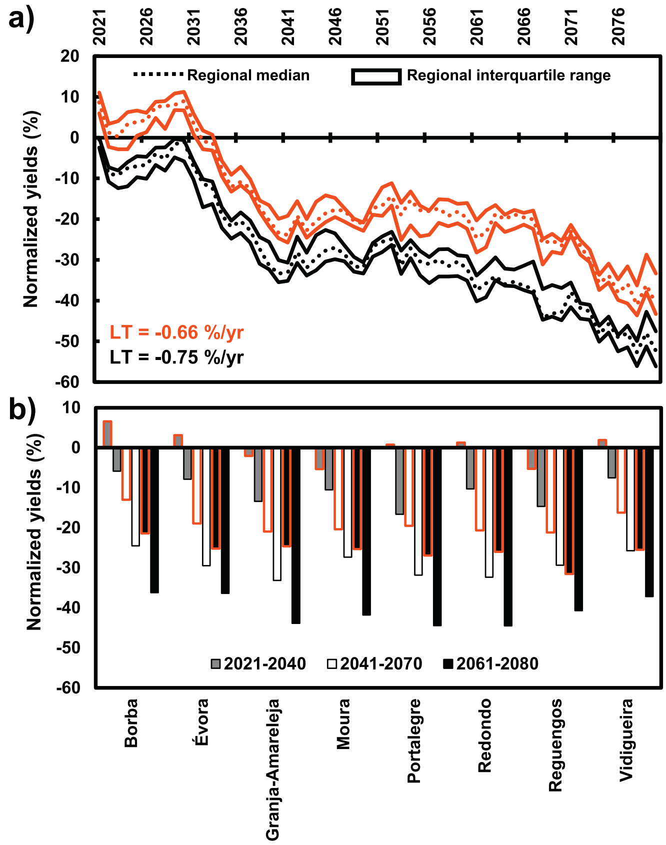

Fig. 3. a) Comparison between normalized yields for mulching (red) and non-mulching (black) simulations. Regional median and interquartile ranges over the full future period (2021–2080) are shown along with the respective linear trends (LT). Normalization was performed using non-mulching simulation maximum yields. b) Same as (a) but for each future sub-period (2021–2040, 2041–2060, 2061–2080) and for each sub-region in Alentejo. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

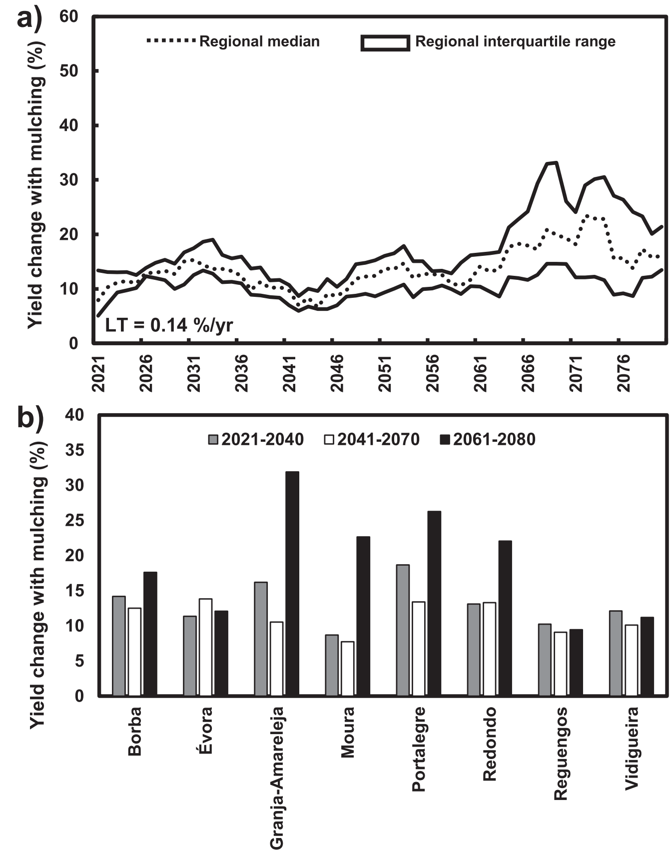

Fig. 4. a) Yield differences after mulching application, i.e. mulching simulations minus non-mulching simulations. Regional median and interquartile range over the full future period (2021–2080) are shown along with linear trend (LT). b) Same as (a) but for each future sub-period (2021–2040, 2041–2060, 2061–2080) and for each sub-region in Alentejo.

decreasing trend of −0.75%/year (Fig. 3a; black). Nonetheless, a distinct behavior is found in the first decade of the simulations. After a sharp decrease in the first years, an increase in yields is projected until 2031. This is undoubtedly related to the decrease in temperatures projected for that specific period by the climate model. Following this atypical yield rise, a clear decrease in yields is projected until 2041. A relative stabilization in yields is apparent until the mid-21st century, which may be attributed to less severe hydric stress projected for this time-period. From this time until 2080 a decrease in yields is still found, though much less noticeable than in the first half of the full period.

Fig. 3b (black) shows the non-mulching yield projection divided into three 20-years sub-periods and for each sub-region in Alentejo. For the first period, the most affected regions are Portalegre, Reguengos and Granja-Amareleja, with yield reductions of approximately −15% (accumulated over 20 years). For the second and third periods, Portalegre, Granja-Amareleja and Redondo are projected to have more severe yield reductions of −35% and −45%, accumulated over 40 and 60 years, respectively. Conversely, the less affected sub-region will be Borba, with yield reductions of −5%, −25% and −35%, respectively. It is also possible to infer that the second time period (2041–2060) will have the strongest negative impacts on yields throughout Alentejo, also given the strong decrease in yields during this period.

3.3. Mulching application under climate change

Fig. 4a shows the mulching adaptation potential for 2021–2080, i.e. the differences in yields between mulching and non-mulching experiments. The results clearly show that mulching application may improve yields. Furthermore, the time series reveals that this beneficial effect will enhance gradually with time, showing a positive significant LT = 0.14%/year. The median yield increase due to mulching will be of around 10% for the first 40 years of simulation. However, for the final 20-year period, both the median and interquartile range will increase, thus suggesting higher benefits in this time period (~25%), though with higher spatial heterogeneity. When comparing these beneficial impacts at a sub-regional level, it can be noticed that the previously mentioned most affected regions by future yield losses, i.e. Granja-Amareleja, Portalegre and Redondo, will present the highest benefits. Furthermore, it is clear that yield increases (due to mulching) over the period of 2061–2080 will surpass those of the previous periods. These results may indeed be explained by the stabilization in the hydric indices during this period. It should be noted that while several mulching types were tested, only the type ensemble average was shown herein, as the simulated differences in yields are not significant (coefficient of variation of 3%). These low differences may be attributed to both limitations of the STICS model and/or to the similar dry matter amounts of the different mulch types.

3.4. Mulching vs. non-mulching simulations

Fig. 3a also shows the comparison between non-mulching and mulching simulations for yields over the full period for Alentejo. It is clear that mulching may not only improve future grapevine yields in Alentejo, but also reduce the long-term decreasing trend until 2080.

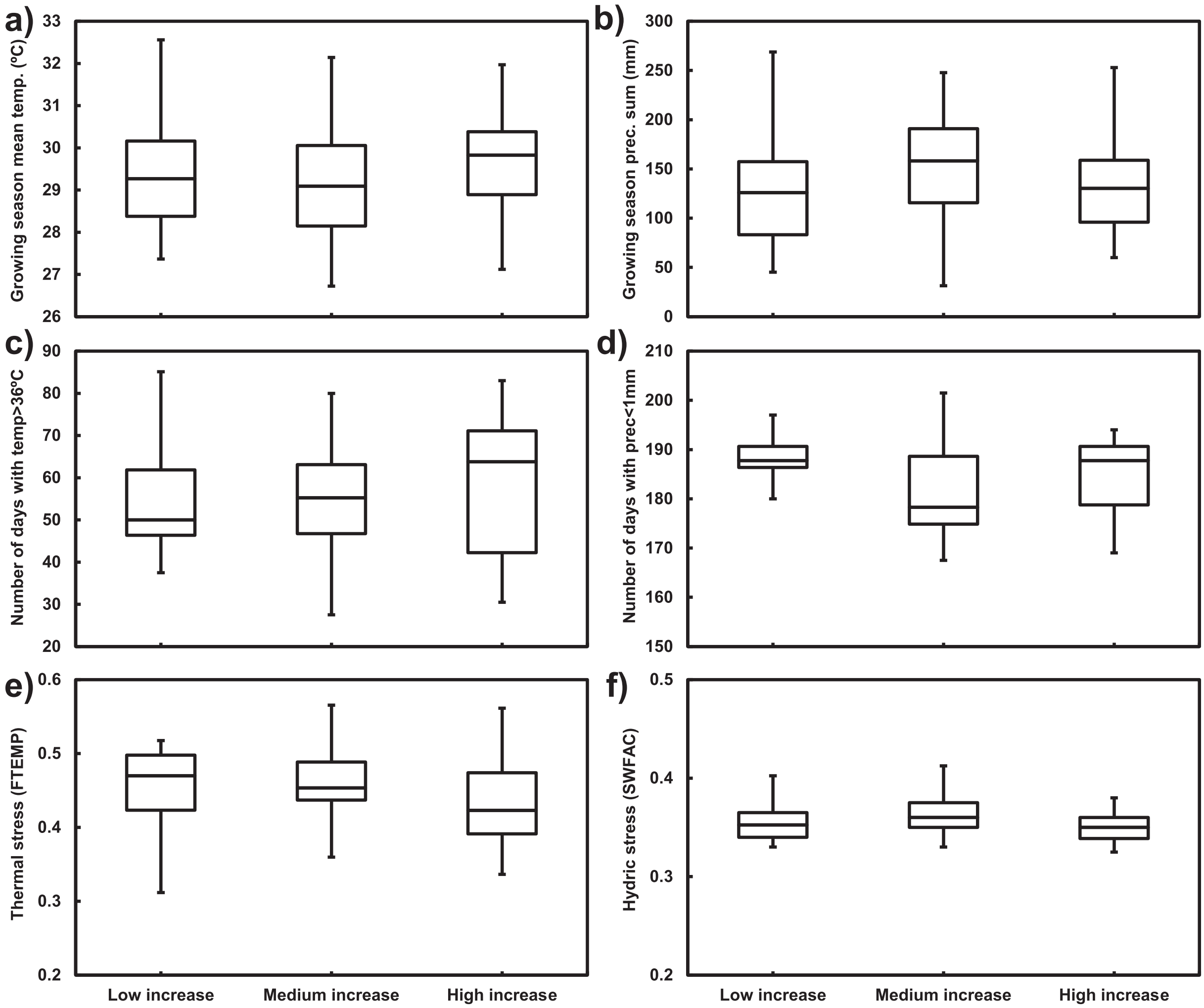

Fig. 5. Box-plots for a) growing season mean temperature; b) growing season precipitation sum; c) number of days with temperature above 36 °C; d) number of days with precipitation below 1 mm; e) thermal stress index (FTEMP); f) hydric stress index (SWFAC) corresponding to years with low, medium and high yield increases when mulching is applied.

Although there is still a decreasing trend in mulching simulations (LT = −0.66%/year), there is an important trend reduction. In fact, for the first decade of mulching simulations (2021 − 2030), yields are indeed projected to increase, rather than decreasing, as is projected by the non-mulching simulations. While median yields show a decrease of more than −50% until 2080 in non-mulching simulations, it is limited to −40% in mulching simulations.

At a sub-regional level, the potential benefits of mulching are also evident (Fig. 3b; red). As expected, a gradual yield loss mitigation is found throughout the time period. For the first 20-year period (2021–2040), nearly all regions show potential yield increases, apart from Granja-Amareleja, Moura and Reguengos. For the second (2041–2060) and third (2041–2080) periods, the mitigation effect is still evident, though all regions are still projected to have lower future yields.

3.5. Mulching under different climatic conditions

Fig. 5 compares the potential yield increases using mulching against different bioclimatic conditions. As previously mentioned, the 60 year time series (2021–2080) of yield differences between mulching and non-mulching simulations was divided into three 20-year classes: high, medium and low yield increases. Box-plots depicting 20-year median, interquartile ranges and minima/maxima are shown for each class and for each index (GST, GSP, T36, PR1, SWFAC, FTEMP) separately. The highest yield increases derived from mulching application occur in years with warmer conditions throughout the grapevine growing season (Fig. 5a). Additionally, higher mulching benefits also occur under conditions of more extreme heat days (Fig. 5c), though there is a higher uncertainty under these heat stress conditions (Fig. 5e). Regarding hydric indices, mulching benefits will be greater under higher stress conditions throughout the growing season (Fig. 5b), and will also be of foremost importance under conditions of extreme drought (Fig. 5d and f). Under lower water stress conditions, mulching may not provide a significantly clear benefit (yield increase).

4. Discussion

Climate change projections for the next decades are expected to bring important challenges to the Portuguese viticulture. In particular, for Alentejo, one of the most renowned winemaking region of the country, future projections hint at a general increase in temperatures and a decrease in water availability (Fraga et al., 2018; Hannah et al., 2013; Kottek et al., 2006; Toth and Vegvari, 2016). Furthermore, a higher frequency of occurrence of extreme weather events (Giorgi and Lionello, 2008; Strandberg et al., 2015), e.g. prolonged heatwaves and drought periods, storms and hailfall, are also projected for this region. The enhanced stress conditions for grapevine growth are expected to

impact grapevine physiological processes, which may ultimately affect yields (Costa et al., 2016; van Leeuwen and Darriet, 2016).

The present study assesses, at a sub-regional level, the importance of mulching as a potential adaptation measure to ensure the future sustainability of grapevine yields in Alentejo. Although several studies showed that mulching can indeed improve yields in regions under low water availability (Chan et al., 2010; DeVetter et al., 2015; Dilley and Nonnecke, 2007; Judit et al., 2011), the assessment of the benefits of mulching under climate change scenarios was, to our knowledge, not previously performed. The STICS process-based crop model was used to simulate future (2021–2080) grapevine yields in the 8 sub-regions of Alentejo. Simulations comprise both non-mulching and mulching model runs under the climate change scenario RCP8.5 (IPCC, 2013). Several mulching types and amounts were tested and compared against non-mulching simulations. This assessment was performed comparing yield changes against different bioclimatic indicators, which encompass grapevine growing season climatic conditions, extreme weather conditions and plant physiological stress factors. Furthermore, the beneficial impacts of mulching on yields are assessed taking into account the annual to decadal variability in climatic conditions.

While both non-mulching and mulching simulations suggest a gradual yield decrease over the future, mulching alleviates some of the detrimental climate change impacts by 10 to 25% (Fig. 4), depending on the sub-region and time period. The results show that mulching can reduce the projected decreasing trend (from −0.75%/year to −0.66%/year), which will help maintaining sustainable annual yield levels (Fig. 3). In fact, mulching is expected to provide yield gains over the full simulated time period, though the benefits should be more evident in the long-term (2061–2080). However, it should be noted that a stabilization in the hydric indices is projected by the climate model in this period. At a sub-regional level, the inner-most regions, i.e. Granja-Amareleja, Portalegre, Reguengos and Redondo, are expected to suffer the highest negative impacts on yields and mulching may then have an important adaptation potential. This assumption is partially corroborated by the computed bioclimatic indicators (Fig. 5). When mulching is applied, the highest yield increases occur in the warmest years and with more extreme heat days (Fig. 5a, c and e). Nonetheless, a clear distinction of mulching benefits at different water stress levels was not clear (Fig. 5b, d and f), particularly given the high water stress levels (SWFAC < 0.35) across all year classes (Fig. 5f).

Our results highlight the importance of water availability as a widely recognized main limiting factor for grapevine productivity under Mediterranean-like environmental conditions (Keller, 2010b). It has been previously shown that the Alentejo winemaking sector will require suitable adaptation measures to cope with the harmful impacts of climate change. For instance, Fraga et al. (2018) suggested irrigation as a suitable adaptation measure (when water is available), though it solely may not be enough to maintain current yields. Hence, a combination of adaptation measures might be required and mulching may be considered a strong candidate. Mulching is a relatively cost-effective strategy, which can be applied by grapevine growers on the short-term. Other adaptation measures should also be envisioned, such as the adoption of training systems that support shorter trunks (e.g. *gobelet*), selecting more drought-tolerant varieties/rootstocks/clones (Bota et al., 2016; Duchene et al., 2010; Harbertson and Keller, 2012; Keller et al., 2011) and adjusting soil management practices (Bahar and Yasasin, 2010; Kvaternjak et al., 2008).

Although the results highlight the benefits of vineyard mulching under climate change, some uncertainties must be discussed. These should be considered regarding the current limitation in both the crop model simulations and climate model projections. Regarding STICS, our experiments revealed small differences owed to the type and amount of mulching, which may indicate model limitations. STICS considers several processes regarding mulching (Brisson et al., 2008): 1) dynamics of plant mulch and proportion of soil cover; 2) modification of surface run-off due to the presence of obstacles located on the surface; 3) water interception by the mulch and its direct evaporation (in relation to the energy balance calculations); 4) decrease in soil evaporation induced by the presence of mulch; 5) effects of these modified fluxes on plant water requirements; 6) modifications in crop temperature linked to changes in the fluxes and albedo of the soil surface; and 7) dynamics of mulching and soil cover ratio. Nevertheless, STICS still has some limitations regarding the mineralization processes when organic mulches are applied (Brisson et al., 2008). In reality, organic mulch retain soil nutrients, but it can also release nutrients into the soil, which is a limitation of STICS.

Additionally, it should be highlighted that STICS simulations take into account the beneficial effects of higher atmospheric CO_2 in the future. This feature will increase water productivity, despite the projected decrease in precipitation. Fraga et al. (2016) demonstrated that this effect partially mitigates future yield losses, which would be higher if this effect was not taken into account. However, some studies indicate that the beneficial effects of higher CO_2 concentrations may be lower in the long-term, particularly for perennial plants/crops (Korner et al., 2005). As such, it is possible that future yield decreases are underestimated.

Although multi-model ensembles are generally preferable (Knutti et al., 2010), the projection presented herein is in agreement with a larger ensemble of models provided by the EURO-CORDEX project (Jacob et al., 2014). The long term trends for atmospheric factors relevant for viticulture/agriculture (e.g. air temperature, precipitation) are vastly similar to other EURO-CORDEX models, as well as the model ensemble mean, for the Alentejo region (Kotlarski et al., 2014). Furthermore, the MPI-M-MPI-ESM-LR GCM has previously shown to be among the more skillful models at replicating atmospheric mechanisms in Western Europe (Santos et al., 2016). Although a more severe future scenario was selected (RCP8.5), the pathways between RCP8.5 and more moderate scenarios (e.g. RCP4.5) clearly diverge only in the last decades of the century, which were not considered in the present study.

5. Conclusions

The results presented herein indicate that, when unmitigated, Alentejo grapevine yields are projected to decrease drastically under a severe future scenario. Given these future projections, suitable adaptation measures need to be outlined by the viticultural sector. The present study analyzed the effects of mulching application under future climates, showing that this adaptation measure may indeed mitigate some detrimental climate change impacts on yields. Mulching is a cost-effective adaptation measure that can be easily adopted by growers (either small farmers or large companies) in the short-term. Nonetheless, this measure by itself, may not fully mitigate the projected yield losses and other complementary strategies should be undertaken to warrant a thriving and competitive winemaking industry in Alentejo, also resilient to climate change.

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